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# PREDICTION OF AIRCRAFT CONDENSATION TRAILS
# PROJECT CONTRAILS

Prepared for:
OFFICE OF NAVAL RESEARCH
DEPARTMENT OF NAVY
WASHINGTON 25, D.C.

FINAL REPORT
REPORT NO. VC-1055-P-5
CONTRACT Nonr-1854(00)
31 OCTOBER 1961


CORNELL AERONAUTICAL LABORATORY, INC.
OF CORNELL UNIVERSITY, BUFFALO 21, N. Y.






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# I. INTRODUCTION

Under Contract Nonr-1854(00), the Office of Naval Research authorized the Cornell Aeronautical Laboratory to conduct a study of the basic characteristics of aircraft exhaust condensation trails. The purpose of this research was to (1) evaluate existing methods for predicting contrail occurrence, (2) develop, where possible, refined criteria on which contrail forecasting can be improved, and (3) generate information to assist in the eventual suppression of contrails. This report describes only contrail forecasting aspects of the program (items 1 and 2). It is understood that these results are to be incorporated into an appropriate Navy manual on the subject.

The physical mechanisms underlying the formation of aircraft condensation trails are sufficiently well understood that reasonably accurate forecasts of the occurrence of contrails can be made when atmospheric pressure, temperature and relative humidity at flight level are known. If any of these parameters are in doubt, as is generally the case, prevailing weather patterns can often provide supplementary data to improve confidence in contrail forecasts.

An established technique for predicting the occurrence of contrails was presented in Air Weather Service Manual 105-100 (Rev.), "Forecasting of Aircraft Condensation Trails,"[1*] and in the Navy publication NAVAER 50-1P-522, "Condensation Trails."[2] An alternate graphical method is presented herein as well as comments on the validity of these two techniques. It is shown that the visual detection of contrails is particularly dependent on atmospheric viewing conditions, a fact that can occasionally explain supposed discrepancies between contrail prediction and verification.

The persistence of contrails depends primarily on ambient relative humidity, final condensate phase, contrail liquid water content, and atmospheric diffusion characteristics. Methods for incorporating these parameters into a semiquantitative persistence forecast are given.

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*References are listed at the end of this report.

## II. SUMMARY

Results of theoretical and experimental studies regarding the prediction, formation, and detection of aircraft condensation trails are summarized as follows:

1. Laboratory and field experiments show that the well known method[1, 2] for predicting contrail occurrence can be used with confidence by the meteorologist, with the following qualifications:

   a) The $\Delta\omega/\Delta T$ ratio that expresses the decrease in moisture content and temperature in the aircraft exhaust wake is better represented by a value of 0.0295 gm/kg°C rather than 0.0336 gm/kg°C. Critical contrail formation temperaturs ($T_c$) thereby are shifted by approximately 1°C to colder values. Figure 1 has been constructed on the basis of $\Delta\omega/\Delta T = 0.0295$ gm/kg°C.

   b) The criterion for a visible contrail, namely one possessing a water concentration of 0.004 gm/m$^3$, is valid only for idealized conditions of observation. Optimum viewing conditions involve a forward scattering angle of the sun's rays and a contrasting sky background. Under less favorable viewing conditions, a contrail may require upwards of 0.1 gm/m$^3$ of condensate to be visible.

   c) There is strong evidence that the final phase of contrails is not always ice. Contrails that remain in the liquid phase will require colder temperatures ( 2 to 3°C) to satisfy the minimum visibility criterion (.004 gm/m$^3$), and will always be non-persistent.

2. An alternate graphical method for predicting contrails, based on Appleman's theory and yielding the same forecast results, is presented. This graphical presentation is particularly useful for (a) contrail persistence forecasts, (b) expressing contrail density, and (c) illustrating the cloud physics principles involved in contrail formation.

3. Contrail duration is a function of ambient relative humidity, final condensate phase, contrail density, and atmospheric diffusion characteristics. Liquid-droplet contrails will practically always evaporate within a matter of seconds. Contrails consisting of ice particles, the more common situation, will persist for hours if environmental conditions exceed ice saturation i.e., exceed ambient relative humidities of approximately 60 to 70%. (See Table II for exact relative humidity values versus temperature.) When the ambient humidity is less than ice saturation, contrails comprised of ice crystals will sublime in seconds to minutes depending on contrail density. Figure 4 illustrates a useful chart for predicting contrail persistence.

4. Certain recognizable weather patterns offer assistance in the forecasting of contrails where accurate knowledge of temperature and humidity at the pressure level of interest is not complete. Consideration of the following meteorological conditions and geographic climatology offers supplementary information to augment standard prediction techniques, and also provides a guide for the planning of long-range military operations:

A. <u>Good Flight Paths - Generally Unfavorable for Contrail Formation</u>

1. High pressure areas in the upper troposphere and low pressure areas in the lower stratosphere (below 25km).

2. Latitudes north of 50°N in the stratosphere (200-100 mb) during the summer; mid-latitudes between 40 and 60°N at 100 mb during the winter season.

3. South of 35°N in winter and south of 60°N in summer at 300 mb (upper troposphere).

4. On the left side of jet streams looking downstream, 100-300 miles from the jet axis. For "warm" jet streams, the core itself may be included.

5. 10,000 feet or more above the tropopause, temperature criteria for the appropriate level permitting. Dry environment $T_d$ values should be assumed.

6. Areas of negative vorticity advection at 300 mb or where cirrus clouds are absent, temperature criteria permitting

B. Flight Paths to Avoid - Generally Favorable for Contrail Formation

1. Low pressure areas in the upper troposphere and high pressure areas in the lower stratosphere.

2. Entire 200 mb level in winter. At 100 mb, south of 45°N in summer; south of 40°N and north of 60°N in winter.

3. North of 35°N in winter and north of 60°N in summer at 300 mb.

4. On the right side of jet streams looking downstream, up to about 400 miles from the axis.

5. The tropopause level plus or minus about 2000 feet.

6. Areas of positive vorticity advection at 300 mb or where cirrus clouds are present.

## III. CONTRAIL PREDICTION

### 1. Graphical Method Customarily Used

The criteria used for predicting the occurrence of aircraft exhaust contrails are discussed in detail in References 1 and 2, and graphically presented in Figure 1. The curve indicates the "Always," "Possible," and "Never" conditions for contrail occurrence as a function of atmospheric pressure, temperature and relative humidity. Appleman's theory,[3] upon which the graphical analysis is based, involves four basic assumptions:

(1) All heat and water produced by the combustion of fuel are discharged in the exhaust with their subsequent dilution being due entirely to mixing with ambient air.

(2) The initial phase of condensed moisture is always liquid.

(3) The final phase of condensed moisture is always ice.

(4) The minimum water content of a barely visible trail is 0.004 $gm/m^3$. (Because of the difference in vapor pressures over water and over ice, all contrails that freeze will achieve this threshold liquid water content.)

From assumption 1, it was shown that the change in mixing ratio, $\Delta\omega$, in the aircraft wake is directly proportional to the change in wake temperature, $\Delta T$. The proportionality constant is a property of the fuel alone and is given by

$$\frac{\Delta\omega}{\Delta T} = 1000\,\frac{W c_p}{H} \text{ gm per kg °C}$$

where $W$ is the mass of water produced by the combustion of one gram of fuel, $c_p$ the specific heat of air at constant pressure, and $H$ the heat of combustion of the fuel. The value of $\Delta\omega/\Delta T$ used in References 1 and 2 was 0.0336 gm/kg °C. More recent specifications of aircraft fuel properties indicate that a ratio of 0.0295 gm/kg °C is more representative, and that value has been used for constructing the well known solid

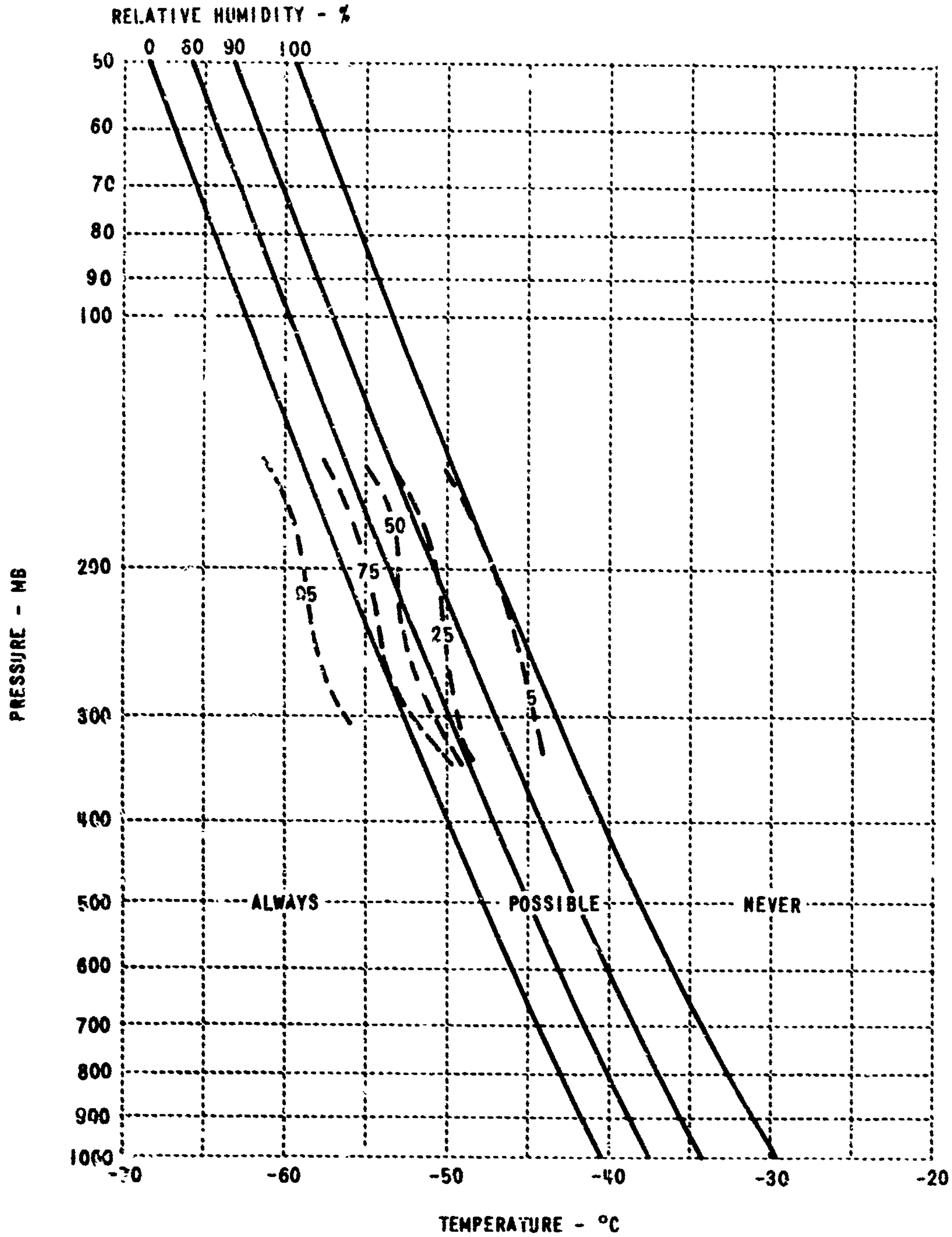



Figure 1 CONTRAIL FORMATION AS A FUNCTION OF PRESSURE, TEMPERATURE AND RELATIVE HUMIDITY OF THE ENVIRONMENT. DASHED LINES ARE EMPIRICALLY DERIVED CURVES OF CONTRAIL PROBABILITY IN PER CENT AS OBTAINED BY PROJECT CLOUD TRAIL.

curves of Figure 1. Numerical values of critical contrail formation temperature are also listed in Table I. The dashed lines in Figure 1 are empirically derived curves of contrail probability in percent as obtained by Project Cloud Trail.

## 2. Alternate Graphical Solution

A contrail prediction diagram, which provides identical results as the first method but contains additional information about trail characteristics, is illustrated in Figure 2. The solid curved line in the phase diagram represents saturation mixing ratio (relative to water) versus temperature at 300 mb. The straight lines having $\Delta\omega/\Delta T$ slopes of 0.0295 gm/kg °C indicate changing conditions of temperature and moisture in the aircraft exhaust wake as mixing with the environment progresses. Mixing will progress until the wake has reached ambient temperature and humidity.

Consider an aircraft flying through ambient air characterized by Point $P$ (-51°C, 80 percent R.H.) in Figure 2. To reach Point $P$, it can be seen that the air-exhaust mixture will exceed water saturation, and hence a contrail will be formed. An indication of the density (water content) of the contrail is given by the degree to which water saturation is exceeded, i.e., the vertical separation distance $\Delta\omega_L$ between the water saturation curve and the straight line depicting wake conditions. $\Delta\omega_L$ expresses the maximum concentration of condensable water vapor in the exhaust wake.

Now consider ambient conditions represented by Point $P'$ (-45°C, 50 percent R.H.). The straight line depicting aircraft wake conditions does not cross the saturation curve in reaching $P'$. Thus, the wake remains subsaturated with respect to water and contrails cannot form.

Threshold or critical conditions for contrail formation are represented by a line tangent to the saturation mixing ratio curve. In a saturated atmosphere, the warmest temperature that will permit contrail formation is $T_c$, which corresponds to the point of tangency of the two curves. For a perfectly dry atmosphere, contrail occurrence would require temperatures colder than $T_d$, the temperature at which the tangent line crosses the zero-humidity axis.

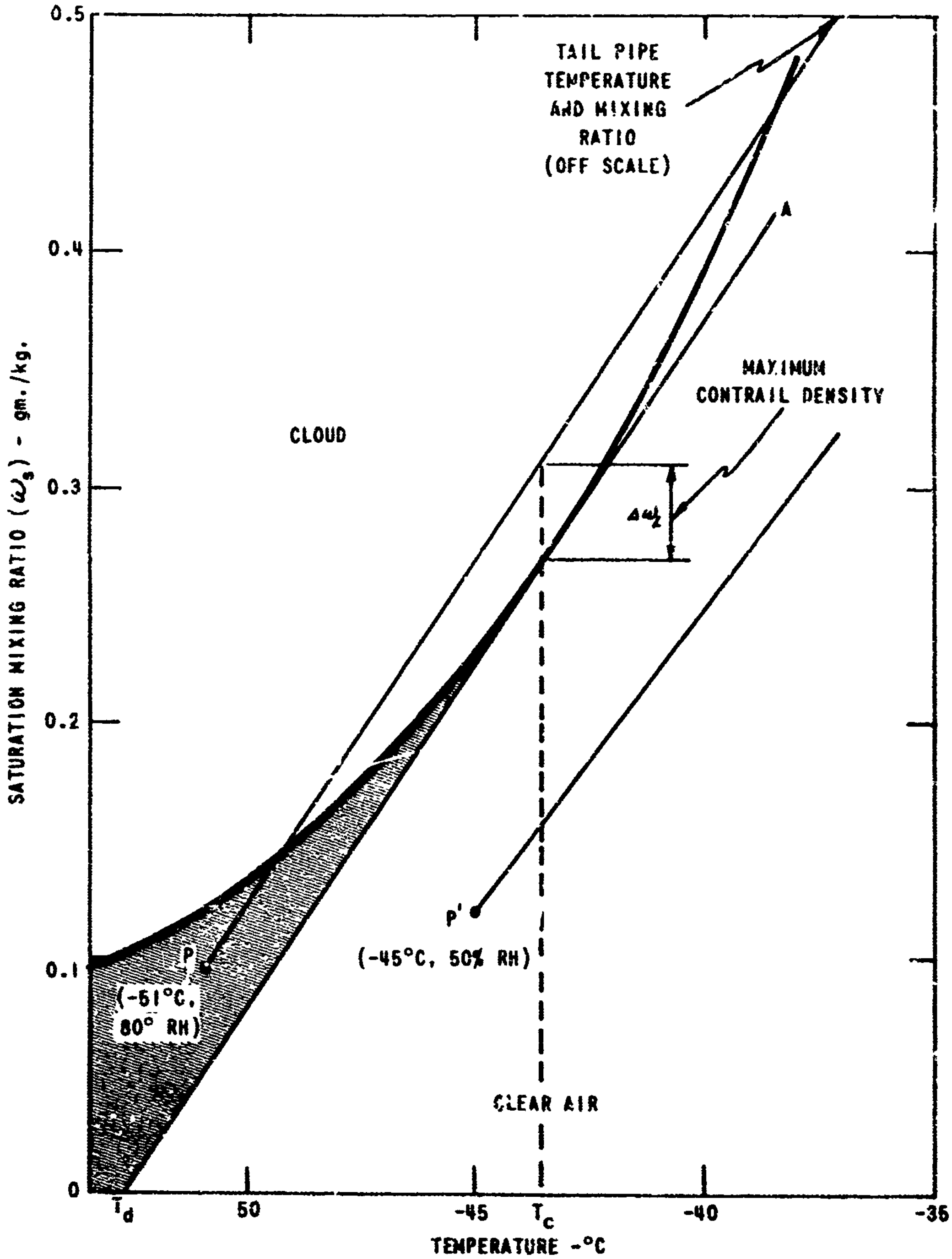
TABLE I

CONTRAIL FORMATION TEMPERATURES - NEGATIVE °C

$\Delta\omega/\Delta T$ = 0.0295 gm-kg°C UNLESS OTHERWISE INDICATED

| PRESSURE | RELATIVE HUMIDITY - PERCENT | | | | | | $\Delta\omega/\Delta T$=0.0336 | |
|---|---|---|---|---|---|---|---|---|
| (mb) | 0 | | 60 | 90 | 100 | | 0% | 100% |
| 1000 | 40.6 | (40.7)* | 37.7 | 34.5 | 29.9 | (31.5)* | 39.2 | 28.9 |
| 900 | 41.9 | (42.0) | 38.9 | 35.6 | 31.2 | (32.9) | 40.3 | 30.0 |
| 800 | 43.2 | (43.3) | 40.2 | 36.9 | 32.7 | (34.4) | 41.7 | 31.3 |
| 700 | 44.5 | (44.7) | 41.5 | 38.3 | 34.3 | (36.2) | 43.0 | 32.9 |
| 600 | 46.0 | (46.2) | 43.1 | 40.0 | 36.1 | (38.0) | 44.7 | 34.6 |
| 500 | 47.8 | (48.0) | 45.0 | 42.0 | 38.2 | (39.9) | 46.5 | 36.7 |
| 400 | 50.0 | (50.2) | 47.2 | 44.2 | 40.5 | (42.6) | 48.6 | 39.0 |
| 300 | 52.6 | (53.0) | 50.0 | 47.2 | 43.7 | (45.9) | 51.5 | 42.0 |
| 200 | 56.4 | (56.8) | 53.8 | 51.0 | 47.5 | (50.4) | 55.4 | 46.2 |
| 150 | 59.0 | (59.6) | 55.4 | 53.8 | 50.1 | (54.0) | 58.0 | 49.0 |
| 100 | 62.4 | (63.3) | 60.0 | 57.4 | 53.7 | (58.3) | 61.5 | 53.0 |
| 50 | 68.1 | (69.8) | 65.8 | 63.4 | 59.4 | (65.0) | 67.4 | 59.2 |

*( ) $T_c$ VALUE ALLOWING FOR THE PRODUCTION OF 0.004 gm/m$^3$ OF CONDENSATE TO MAKE A NONFREEZING CONTRAIL VISIBLE.




THE CURVED LINE REPRESENTS SATURATION MIXING RATIO VERSUS TEMPERATURE, WHILE THE STRAIGHT LINES INDICATE AIRCRAFT WAKE CONDITIONS RETURNING TO AMBIENT CONDITIONS. CONTRAILS OCCUR WHEN WAKE CONDITIONS EXCEED WATER SATURATION, i.e., WHEN THE STRAIGHT LINES INTERSECT THE SATURATION CURVE. TANGENT LINE A DEFINES THE LOCUS OF CRITICAL CONTRAIL FORMATION TEMPERATURES ($T_c$ FOR 100% RH, $T_d$ FOR 0% RH, AND $T_d < T_i < T_c$ FOR INTERMEDIATE RELATIVE HUMIDITIES).

**Figure 2 300 MB CONTRAIL PREDICTOR DIAGRAM**

At temperatures between $T_c$ and $T_d$, contrail formation is dependent on ambient relative humidity. For example, at -50°C, the relative humidity must exceed 58 percent in order for a contrail to be produced. In short, the hatched area in Figure 2 describes all environmental conditions that will foster contrail formation at 300 mb.

The family of saturation mixing ratio curves for various pressure levels is shown in Figure 3. A separate chart for each pressure level of interest is recommended. Simple construction of a right triangle with appropriate $\Delta\omega/\Delta T$ slope (0.0295 gm/kg °C) will allow ready use of each chart as described above. This type of graphical presentation is advantageous in that it:

(1) clearly illustrates the cloud physics principles involved in contrail formation,

(2) Provides quantitative information on the maximum amount of liquid water comprising the contrail,

(3) Accommodates any fuel characteristics simply by altering the $\Delta\omega/\Delta T$ ratio, and

(4) Lends itself to persistence forecasts (Section IV.).

These charts are intended as a supplement rather than as a replacement to Figure 1.

## 3. Validity of Contrail Prediction Methods

Flight data acquired on Project Cloud Trail, as indicated in Figure 1, generally establish the validity of the forecasting methods previously described. It is evident, however, that contrails were not always observed in the region where theory would dictate that they must form. Principal reasons for this apparent discrepancy are that (1) the visual detection of contrails is dependent on viewing angle with respect to the sun and the background brightness, and (2) the contrails do not always freeze.

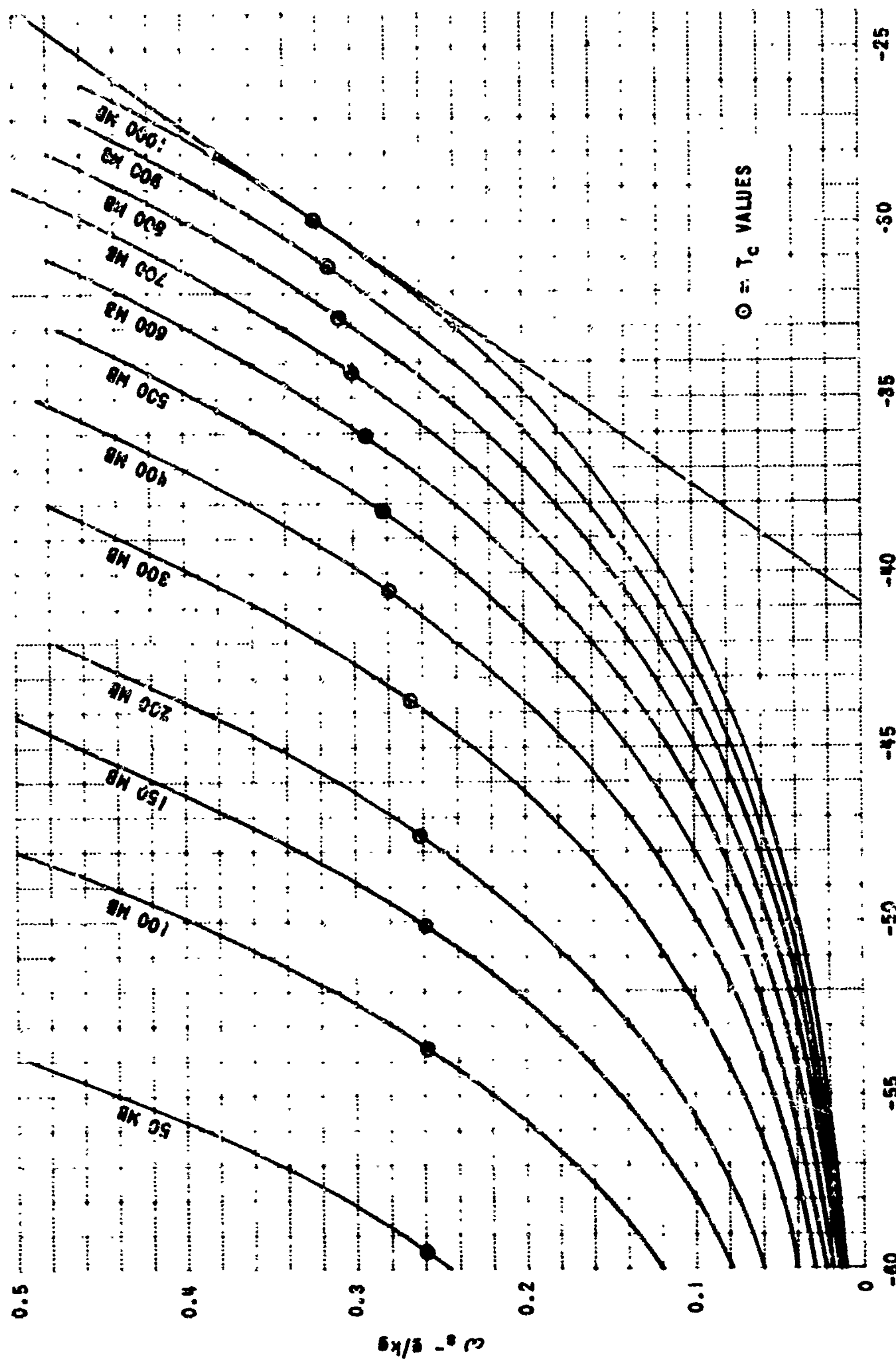



Figure 3 SATURATION MIXING RATIO OVER WATER ($\omega_s$) vs. TEMPERATURE AND PRESSURE

Laboratory studies[4] have shown that a contrail with 0.004 gm/m$^3$ water concentration is visible only under idealized conditions of observation. A contrail is most distinct when seen at a forward scattering angle against a contrasting background. However, under less favorable viewing conditions (for example, at large scattering angles), trail density must be larger by an order of magnitude or more to be visible. This fact has been shown theoretically and experimentally in the above study, and was substantiated by a recent Navy experimental flight[5] in which a continuous circular contrail was formed aloft and then observed with respect to solar position.

The laboratory experiments also provided strong evidence that contrails do not always freeze, especially at relatively warm ambient temperatures close to the $T_C$ point. When contrail droplets do freeze (probably the more common situation), deposition of water vapor onto the ice crystals is sufficient to fulfill the 0.004 gm/m$^3$ visibility criterion. However, if the contrail droplets do not freeze, contrails can only be produced at ambient temperatures cold enough to provide the necessary amount of observable moisture (0.004 to about 0.1 gm/m$^3$, depending on viewing conditions). The critical contrail formation temperatures would be shifted to colder values; for the minimum visibility criterion (0.004 gm/m$^3$), this shift, as shown in Table I, amounts to 1 to 3 °C at typical jet flight altitudes.

In summary, either of the previous forecast methods will predict the occurrence of contrails at times when (even if P, T, and R.H. data are exactly known) trails will not be observed due to less-than-optimum viewing conditions and the trails not freezing. Since it is generally preferable to err in forecasting in the conservative direction, this trend toward over-forecasting may not be objectionable.

## IV. CONTRAIL PERSISTENCE

The duration of a contrail depends, in estimated order of importance, on ambient relative humidity, final condensate phase, contrail density (water or ice content), and atmospheric diffusion characteristics. Quantitative methods for predicting the persistence of contrails have not been prescribed owing to the uncertainty in accurately expressing these influential parameters.

Contrails that remain in the liquid phase will evaporate within seconds of the aircraft passage, since the relative humidity at upper levels is generally less than 100 percent. Contrails that freeze under atmospheric conditions and that are sub-saturated with respect to ice will usually require a minute or more to disappear depending on degree of sub-saturation, contrail density, and environmental mixing. Contrails that freeze in an ice saturated environment will grow and persist for long periods of time (hours); atmospheric wind shear and turbulence will gradually diffuse the trail.

The mixing ratio - temperature phase diagram can be used to advantage to indicate contrail zones associated with characteristic persistence patterns. Figure 4 is a partial reconstruction of Figure 2 with an ice saturation curve superimposed. As stated previously, the line tangent to the water saturation curve bounds the range of atmospheric conditions that will foster contrail formation. This region has been divided into three zones which can be used as follows:

(a) Zone A -- The region occupied by any contrail that forms in this environment must be supersaturated with respect to ice as indicated by the fact that all environmental conditions represented by points in A lie above the ice saturation curve ( $\omega_{s-i}$ ). If the contrail freezes, it will persist. At temperatures colder than $T_i$ , the boundary of Zone A, the contrail region may either exceed or be less than ice saturation.

(b) Zone B -- The environment is saturated with respect to ice and contrails consisting of ice crystals will persist.

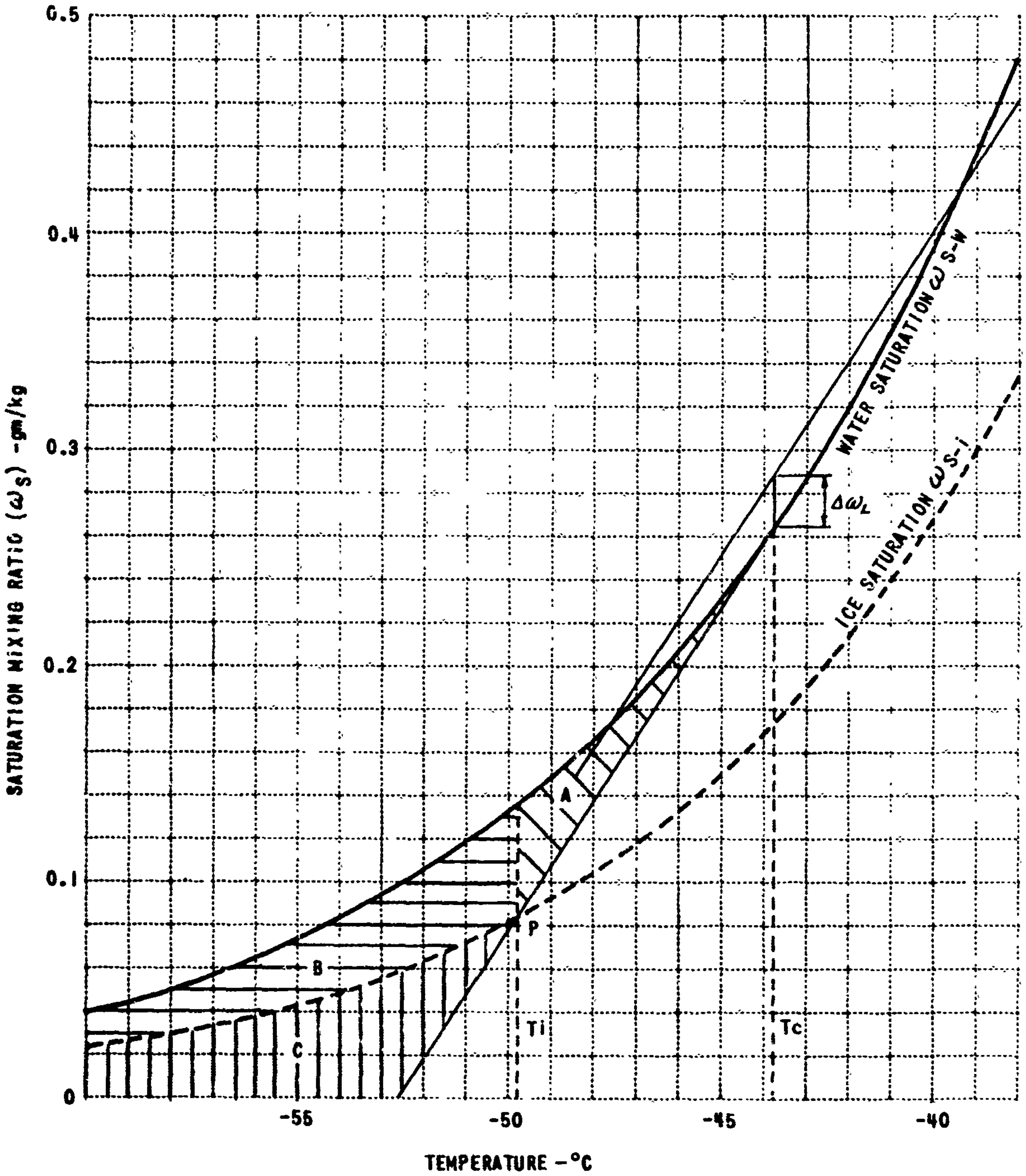



Figure 4 CONTRAIL PHASE DIAGRAM - 300 MB

(c) Zone C -- The atmosphere is sub-saturated with respect to ice and contrails will not persist. Generally speaking, the colder the temperature within Zone C, the more dense will be the contrail, and the longer it will take for the trail to dissipate.

The values of relative humidity with respect to water, for 100 percent relative humidity with respect to ice, are given in Table II as a function of temperature. These values, corresponding to ice saturation $(RH_{s-i})$, can be obtained graphically from Figure 4, where for a given temperature $RH_{s-i} = 100 \frac{\omega_{s-i}}{\omega_{s-w}}$. As shown, ice saturation varies from 75 percent R.H. at -30°C to 55 percent R.H. at -60°C. Thus, contrail persistence or non-persistence can be specified if ambient humidity is known. Though accurate measurements of upper-level humidity are generally not available, inspection of synoptic weather patterns and cloud reports (as discussed in Section V) will often indicate whether the flight level humidity in question is greater or less than ice saturation.

Contrails which do not freeze will always be non-persistent. An absolute prediction of non-freezing contrails cannot be made, although the most probable conditions for such an occurrence can be prescribed. In the absence of freezing nuclei, the spontaneous freezing of supercooled droplets is a statistical event dependent on temperature, drop volume, and cooling rate or exposure time.[6] Relatively warm temperatures, small droplets, and short exposure times tend to discourage freezing.

Referring to Figure 4, it becomes evident that at least the first two of these three conditions are best met by contrails formed close to the maximum formation temperature, $T_C$. As an illustration, Zone A offers a more favorable region for liquid contrails than do Zones B or C. Not only are temperatures warmer but the amount of excess moisture available for condensation is generally smaller and, hence, droplet growth more limited. The exposure time of the condensed droplets to supercooled temperatures, which can be related graphically to the length of the $\Delta\omega/\Delta T$ line above the water saturation curve, will generally decrease as $T_C$ is approached. (The exception to this rule occurs under environmental conditions that are so close to water saturation that an extremely long time is required

TABLE II

RELATIVE HUMIDITY WITH RESPECT TO WATER
AT ICE SATURATION

| TEMPERATURE - °C | RELATIVE HUMIDITY - % |
|---|---|
| -30 | 74.6 |
| -35 | 71.1 |
| -40 | 67.8 |
| -45 | 64.8 |
| -50 | 61.9 |
| -55 | 59.4 |
| -60 | 55.3 |

for mixing to progress to the point where the aircraft wake is no longer saturated relative to water. Thus, exposure time is extremely long and droplet freezing is probable.)

Liquid non-persistent contrails are more apt to occur at lower altitudes where contrail formation at progressively warmer temperatures is possible (see Table I). Conversely, it is reasonably safe to assume that all contrails will freeze that are formed above 150 mb ( $T_C$ values colder than approximately -50°C). (The forecaster should be cautioned at this point that even ice trails formed at 150 mb or higher will usually be non-persistent since the mixing ratio at these altitudes is usually significantly below ice saturation.) Laboratory tests in which miniature contrails were produced in an altitude chamber have shown the occasional existence of non-persistent liquid droplets at temperatures down to approximately -50°C, but the predominant phase of $H_2O$ at temperatures of -50°C or colder was ice in every case.

The effect of fuel exhaust products on droplet purity and freezing is not known, nor are extensive data available on the concentration of freezing nuclei within the contrail wake at flight altitude. Because of these uncertainties and because spontaneous freezing is a probabilistic event, it appears best to adopt the following criteria for forecasting contrail persistence:

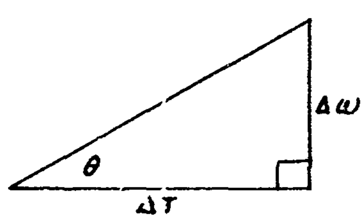
(1) Assume that contrails always freeze (quite certainly the case above 150 mb) and use the phase diagram chart (Figure 4 ) to determine super- or sub-saturation relative to ice. A persistent or non-persistent forecast would be made accordingly.

(2) Qualify a non-persistent forecast by a measure of the concentration of contrail moisture $(\Delta \omega_L)$. Other conditions being equal, contrail dissipation time will increase as $\Delta \omega_L$ increases. The numerical relationship between $\Delta \omega_L$ and contrail decay time awaits the accumulation of well-monitored flight data. An approximate relationship can be obtained by the

field forecaster as experience in using the chart and verification information (ground observations, pilot de-briefing) is acquired.

(3) Recognize that contrails that do not freeze will be non-persistent and will degrade a persistence forecast based on expected ice saturation conditions. Be especially aware of this possibility at contrail formation temperatures within 7°C of $T_C$ at altitudes below 45,000 feet (pressures greater than 150 mb).

**For field use it is recommended that a separate phase diagram similar to Figure 4 be constructed for each pressure level of interest; charts for each 50 mb level between 300 and 100 mb will adequately cover the customary flight altitudes of conventional jet aircraft. Values of saturation mixing ratio over water and ice versus pressure can be obtained from References 7 and 8. A transparent plastic overlay for sketching $\Delta\omega/\Delta T$ lines with an appropriate right triangle, as illustrated below, will add to the chart's utility.**




$$\theta = \tan^{-1} \frac{\Delta\omega}{\Delta T} = \tan^{-1} 0.0295 \ gm/kg\ ^\circ C$$

## V. LONG RANGE (DISTANCE AND TIME) FORECASTING OF CONTRAILS

As discussed in previous sections, the forecasting of condensation trails can be accomplished with reasonable accuracy when ambient pressure, temperature and relative humidity are known. If any of these parameters are in doubt, as is generally the case over a given flight path, prevailing broad-scale weather patterns can often provide supplementary data to enable the making of more positive contrail forecasts. Relationships between condensation trail occurrence and synoptic weather features can also assist in long-range military planning since most weather patterns tend to vary systematically with season and locale.

An investigation of broad-scale weather patterns was made to determine the characteristics of atmospheric regions favorable and unfavorable for the formation of contrails.[9] The investigation was restricted to the 25,000- to 55,000-foot zone (approximately 300-100 mb). Attempts to correlate contrail occurrences with weather patterns on the surface map are unrealistic; synoptic features at the surface and aloft often behave independently of one another, and air mass characteristics can change markedly with altitude. Thus, the following features of upper-level weather maps were considered, in terms of typical temperature and humidity characteristics.

(1) upper-level pressure cells
(2) jet streams
(3) the tropopause
(4) regions of high cloud cover (positive vorticity advection)

Critical contrail formation temperatures for saturated and dry environments, extracted from Table I, appear on the following page for ready reference.

difference between adjacent pressure cells is appreciable, 10°C to 15°C not being an extreme differential. For example, fifty mid-latitude soundings made during the winter season showed average 200 mb ridge, and adjacent trough, temperatures of -66°C and -48°C respectively.[10] Therefore, at a given pressure level, a ridge may give rise to contrail occurrence whereas a trough may be completely free of trails.

An analysis of mean global temperature patterns on a seasonal basis can be made from appropriate upper-level charts. From average temperature values over the northern hemisphere at 300, 200, and 100 mb, the following regions <u>unfavorable</u> for contrail formation can be delineated:

(a) In the vicinity of low pressure cells or troughs in the lower stratosphere and near high pressure cells or ridges in the upper troposphere,

(b) South of 35°N in winter and south of 60°N in summer at 300 mb,

(c) North of 60°N in summer at 200 mb,

(d) North of 53°N in summer and between 40 and 60°N in winter at 100 mb.

In effect, the above areas represent the warmest regions at a given pressure level. By delineating the "cold spots" in a similar manner, areas most conducive to contrail formation can be described. (See Summary, page 4.) Since the thermal forecast aids presented are based on average temperature conditions, a meteorologist must excercise discretion in applying such rules when atypical conditions are met.

## 2. The Jet Stream

A number of investigators have noted the higher incidence of clouds and increased moisture on the right-hand side of jet streams looking downwind (high pressure side). It is, therefore, tempting to conclude that aircraft hoping to avoid contrails should select flight paths on the left side of a jet stream. This conclusion is generally correct for stratospheric

flights, but it is invalid for levels below the tropopause where the left-hand side of the jet is considerably colder than the right. Consequently, the lower temperatures often give rise to conditions suitable for contrail formation, despite the dryer environment.

The frost-point hygrometer work of R. Murray[11] confirms the expected moisture gradient across jet streams. At the level of the jet stream, the average relative humidity with respect to ice was found to be 50 percent at 250 to 300 miles from the jet stream axis on the high pressure side, and only about 10 percent at the same distance on the low pressure side. Though considerable variation in humidity was noted, cloud cover was very rare on the low pressure side at distances exceeding 100 nautical miles. The jet stream core itself was found to cover a wide humidity range, dry cores being associated with relatively warm jets and moist cores with relatively cold jets. Average values for a small sampling of six cases showed "warm" jet stream temperatures to be -45°C with a frost-point depression of 17.8°C; "cold" jet streams possessed average temperatures and frost-point depressions of -55.5°C and 5.0°C respectively.

From the foregoing paragraphs it can be concluded that aircraft flying in the stratosphere on the left side of jet streams (looking downstream) at distances of 100 to 300 miles from the jet axis stand an excellent chance of not forming contrails. This "safe" zone may be expanded to include the jet core itself, in the case of relatively warm jet streams.

## 3. The Tropopause

The tropopause slopes irregularly from a low height at the pole (20 - 30,000 feet) to a maximum height at the equator (50 - 60,000 feet). Atmospheric temperatures drop off with altitude until the tropopause is reached, above which temperatures commence to rise, or remain quasi-isothermal for a short distance and then rise. Therefore, on any given vertical cross section, the coldest layer of air is usually found at the tropopause or slightly above it. The tropopause inversion also tends to

cap the upward flux of water vapor so that relatively high concentrations of moisture often exist just below the tropopause base. This combination of low temperature and high relative humidity makes the immediate tropopause region generally conducive to contrail formation.

Humidity measurements made with a frost-point hygrometer have indicated that at elevations exceeding 5000 to 10,000 feet above the tropopause, the relative humidity with respect to ice is less than 1 percent.[12] Applying this information to contrail forecasting, we may tentatively conclude that at 100 mb and sometimes at 200 mb, depending on tropopause height, the dry environment can be safely assumed and contrails will form only if the temperature is colder than the $T_d$ values in Table I.

Mean temperature charts show that at the intersection of the 200 mb surface with the tropopause, the average temperature is about -53 to -56°C. As a result, the intersection region (approximately 30°N in winter and 45°N in summer) is very favorable for contrail formation. Consequently, aircraft hoping to elude detection from ground observers should routinely avoid the tropopause level

## 4. Regions of High Cloud Cover (Positive Vorticity Advection)

It is fairly obvious that extensive cloud cover at any level is indicative of a relatively moist environment; however it is not so obvious that the changing quality of clouds provides approximate quantitative data concerning ambient relative humidity. Where cirrus clouds are present, but are neither growing nor dissipating appreciably, a relative humidity of 100 percent with respect to ice can be assumed at cloud level. This corresponds to a relative humidity with respect to water of about 70 percent at -35 to -40°C. If the cirrus clouds are thickening and growing, atmospheric conditions must be super-saturated with respect to ice so that a relative humidity of 80 to 90 percent would be more representative Similarly, dissipating cirrus decks would indicate an ambient relative humidity less than 70 percent. Therefore, the presence and growth characteristics of cirrus clouds offer

the forecaster a good approximation of moisture conditions aloft. This information, when coupled with air temperatures as indicated by radiosonde or pilot reports, can appreciably improve a contrail forecast based on ambient temperature alone.

French and Johannessen[13] have correlated the occurrence of cirro-stratus clouds with vorticity patterns at 300 mb. Their study disclosed that 86 percent of extensive cloud layers above 25,000 feet were located in areas of positive vorticity advection. Consequently, 300 mb positive vorticity advection patterns generally indicate regions of relatively high moisture contents aloft. This rule-of-thumb, though valuable where little other humidity or cloud information is available, includes a fairly wide humidity range. On the average, 50 percent of the 300 mb map area indicated positive vorticity advection whereas only about 20 percent of the map showed extensive high clouds. Of more value are the smaller areas of negative vorticity advection which were generally free of cloud cover, indicative of a relatively dry environment, one adverse to contrail formation.

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